STONE & WEBSTER ENGINEERING CORPORATION

CALCULATION INDEX

▲ 5010.45 B

CLIENT:	PROJECT:	J.O./W.O. NUMBER:	PREPARING STAFF GROUP/PROJECT DISCIPLINE:	PAGE 1 OF
IP&L	FGD S Buffering Agent Additive Test	12800.15	POWER DIV., PROCESS GROUP	

CALCULATION NUMBER	CALCULATION TITLE	Q.A. CAT.	PREPARER/DATE / REVIEWER(S)/DATE	CONFIRMATION REQUIRED * YES	CONFIRMATION REQUIRED * NO	SUPERSEDED / SUPPLEMENTED BY	FILING LOCATION
PP(B)-001	Water Capacities of FGD System Tanks	N.A.	S.On 5/4/84	—	x		
PP(B)-002	Estimate Initial Test Conditions for Sizing Additive Feed Pump	N.A.	S.On 5/4/84	—	x		
PP(B)-003	- NOT USED -			—	—		
PP(B)-004	General Solutions to Concentrations as f(t)	N.A	S.On 5/11/84	—	x		
				—	—		
				—	—		
				—	—		

* CONFIRMATION OF INPUTS AND/OR ASSUMPTIONS AS INDICATED IN THE CALCULATION

CALCULATION SUMMARY
▲ 5010.47

CALCULATION NO.	DATE	PAGE
PP(B)-004	5/11/84	1 of 13

CLIENT: Indianapolis Power & Light Company, Petersburg Station Unit 3
FGD System Buffering Agent Additive Test and Process Evaluation

J. O. NUMBER: 12800.15

SUBJECT: General Solution to Concentrations as f(t)

PROBLEM:
Obtain general solutions of concentration of additive in recycle tanks and FGD system

AUDIT REMARKS

CHECKER'S REMARKS:

APPROACH/ASSUMPTIONS:
Solve simultaneous differential equations

AUDIT REMARKS

CHECKER'S REMARKS:

SOURCES—DATA/EQUATIONS:
General principles - use balances on additive
1) around recycle tanks
2) around rest of FGDS

AUDIT REMARKS

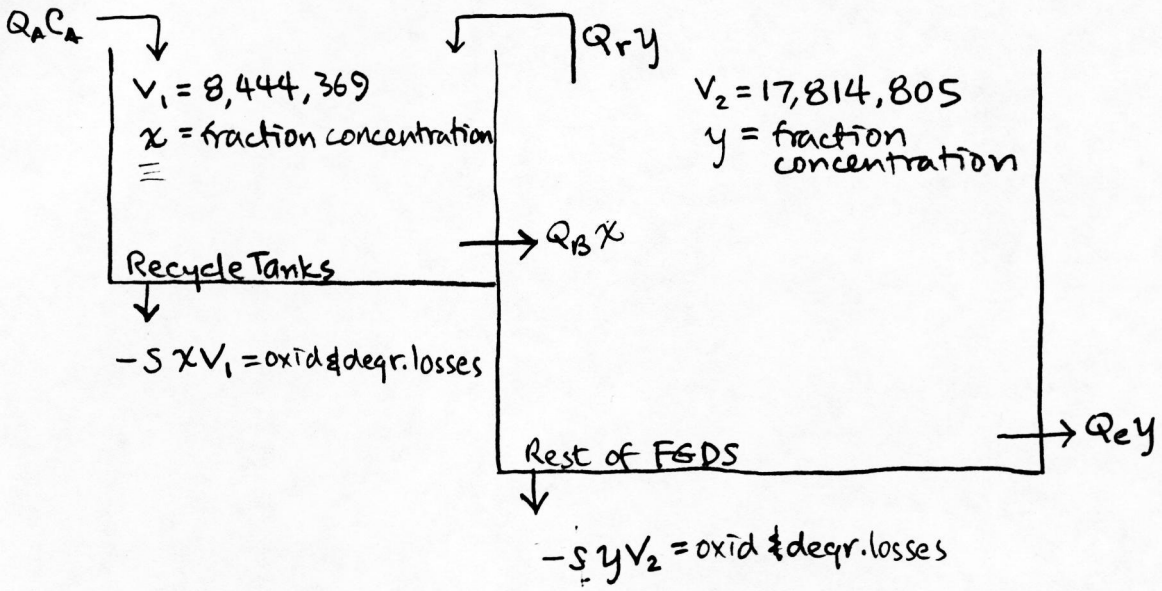
CHECKER'S REMARKS:

CONCLUSIONS:
Additive Concentration in "rest of FGDS" = y(t) on p5
Additive concentration in recycle tanks = x(t) on p7
Specific cases: I - steady state at x = 500ppm pp8-9.
II - stop feed - observe decay of concentration.

AUDIT REMARKS

CHECKER'S REMARKS:

AUDIT SUMMARY			
CHECKS	CORRECTIVE ACTION TAKEN BY	CALCULATED BY	DATE 5/11/84
INFRACTIONS	DATE	CHECKED BY	DATE
		AUDITED BY	DATE



Additive balance around recycle tank:
in − out = accumulation

$$Q_A C_A + Q_r y - Q_B x - S x V_1 = V_1 \frac{dx}{dt}$$

Additive balance around rest of FGDS
in − out = accumulation

$$Q_B x - Q_r y - Q_e y - S y V_2 = V_2 \frac{dy}{dt}$$

Rearrange both equations:

$$-Q_r y + V_1 \frac{dx}{dt} + (Q_B + S V_1) x = -Q_A C_A \; ; \quad V_2 \frac{dy}{dt} + (Q_e + Q_r + S V_2) y - Q_B x = 0$$

Using simple coefficients

$$a y + b \frac{dx}{dt} + c x = f \qquad g \frac{dy}{dt} + h y + k x = 0$$

where known constants are:

$a = -Q_r$ = water returned to recycle tanks from dewatering, lb/hr (-1)

$b = V_1$ = lb water in recycle tanks

$c = Q_B + S V_1$; where Q_B = water blowdn from recycle tanks, lb/hr
S = fraction lost per hour to oxid & degradation

$f = Q_A C_A$ = lb/hr additive in feed from storage tank-truck.

$g = V_2$ = lb water in rest of FGDS

$h = Q_e + Q_r + S V_2$; where Q_e is water leaving FGDS permanently (i.e., water in filtercake, or thickener underflow if filtrate is not returned to FGDS).

$k = -Q_B$

$y = f(t)$

from p2 l 30

$$a y + b\frac{dx}{dt} + c x = f \qquad g\frac{dy}{dt} + h y + k x = 0$$

In linear differential operator form:

$$a y + (bD + c)x = f \qquad (gD + h)y + kx = 0$$

First eliminate x terms: $\times k$ $\qquad \times (bD+c)$

$$aky + k(bD+c)x = kf \qquad (bD+c)(gD+h)y + (bD+c)kx = 0$$

subtract 2 eq's

$$aky - (bD+c)(gD+h)y = kf$$

multiply out

$$(bD+c)(gD+h)y - aky + kf = 0$$

$$(bgD^2 + cgD + bhD + ch)y - aky + kf = 0$$

$$bgD^2y + cgDy + bhDy + chy - aky + kf = 0$$

collect D^2, D, c's

$$[\underbrace{bg}_{\alpha} D^2 + \underbrace{(cg+bh)}_{\beta} D + \underbrace{(ch-ak)}_{\gamma}]\, y = -kf$$

use simplified constants α β γ

$$[\alpha D^2 + \beta D + \gamma]\, y = -kf$$

The characteristic equation to obtain the homogeneous solution y_H is

$$\alpha r^2 + \beta r + \gamma = 0$$

Since α, β, and γ are known constants, l30 is a quadratic equation in r with roots

$$r_1 = \frac{-\beta + \sqrt{\beta^2 - 4\alpha\gamma}}{2\alpha}$$

$$r_2 = \frac{-\beta - \sqrt{\beta^2 - 4\alpha\gamma}}{2\alpha}$$

These r_1 and r_2 are in the general form of the homogeneous solution

$$y_H = c_1 e^{r_1 t} + c_2 e^{r_2 t} + c_4$$

Since the particular solution y_p = constant (l26 kf = constant)

$y = f(t)$

the complete solution $y = y_H + y_P =$

$$y = c_1 e^{r_1 t} + c_2 e^{r_2 t} + \underbrace{c_4 + y_P}_{\text{constant}}$$

combine constants to get

$$y = c_1 e^{r_1 t} + c_2 e^{r_2 t} + c_3$$

differentiate:

$$\frac{dy}{dt} = c_1 r_1 e^{r_1 t} + c_2 r_2 e^{r_2 t}$$

again:

$$\frac{d^2y}{dt^2} = c_1 r_1^2 e^{r_1 t} + c_2 r_2^2 e^{r_2 t}$$

and substitute into p3 l26 $= [\alpha D^2 + \beta D + \gamma] y = -kf$

$$\alpha c_1 r_1^2 e^{r_1 t} + \alpha c_2 r_2^2 e^{r_2 t} + \beta c_1 r_1 e^{r_1 t} + \beta c_2 r_2 e^{r_2 t} + \gamma c_1 e^{r_1 t} + \gamma c_2 e^{r_2 t} + \gamma c_3 = -kf$$

collect coeff. of exponential terms

$$c_1 e^{r_1 t}(\alpha r_1^2 + \beta r_1 + \gamma) + c_2 e^{r_2 t}(\alpha r_2^2 + \beta r_2 + \gamma) + \gamma c_3 = -kf$$

since the equality is true at all t, each of the coefficients $= 0$, and →

$$(\alpha r_1^2 + \beta r_1 + \gamma) = 0 \qquad (\alpha r_2^2 + \beta r_2 + \gamma) = 0 \qquad \gamma c_3 = -kf$$

we know, then, $c_3 = \frac{-kf}{\gamma} = \frac{-kf}{ch - ak}$ which are known constants (p2 bottom)

Let $\frac{dy}{dt} = 0$ at $t = 0$ from l9 above

$$0 = c_1 r_1 e^0 + c_2 r_2 e^0$$

$$c_2 r_2 = -c_1 r_1$$

$$c_2 = -c_1 r_1 / r_2$$

substitute into l7 above

$$y = c_1 e^{r_1 t} + \left(\frac{-c_1 r_1}{r_2}\right) e^{r_2 t} + \frac{-kf}{ch - ak}$$

$$y = c_1 \left(e^{r_1 t} - \frac{r_1}{r_2} e^{r_2 t}\right) + \frac{-kf}{ch - ak}$$

c_1 is determined by boundary conditions:

$y = f(t)$

from p5, l40:

$$y = c_1\left(e^{r_1 t} - \frac{r_1}{r_2} e^{r_2 t}\right) + \frac{-kf}{ch-ak}$$

at $t=0$ $\quad y_0 = c_1\left(1 - \frac{r_1}{r_2}\right) + \frac{-kf}{ch-ak}$

$$y_0 + \frac{kf}{ch-ak} = c_1\left(1 - \frac{r_1}{r_2}\right)$$

$$c_1 = \left[\frac{y_0 + \frac{kf}{ch-ak}}{\left(1 - \frac{r_1}{r_2}\right)}\right]$$

so the solution is

$$\boxed{y = \left[\frac{y_0 + \frac{kf}{ch-ak}}{\left(1 - \frac{r_1}{r_2}\right)}\right]\left(e^{r_1 t} - \frac{r_1}{r_2} e^{r_2 t}\right) + \frac{-kf}{ch-ak}}$$

where y_0 = initial concentration of "Rest of FGDS"

$\frac{-kf}{ch-ak}$ = final concentration of FGDS $= \dfrac{(-1)(-Q_B)(Q_A C_A)}{(Q_B + sV_1)(Q_c + Q_r + sV_2) - (-Q_r)(-Q_B)}$

r_1 = p3 l34

r_2 = p3 l37

$x = f(t)$

restart on $x = f(t)$

from p3 l8: $\quad ay + (bD+c)x = f \qquad (gD+h)y + kx = 0$

eliminate y terms: $\quad \times(gD+h) \qquad \times a$

$$(gD+h)(ay) + (gD+h)(bD+c)x = (gD+h)f \qquad a(gD+h)y + akx = 0$$

subtract 2 eqs

$$(gD+h)(bD+c)x = (gD+h)f + akx$$

$$bgD^2 + hbD + cgD + chx - gDf - hf + akx = 0$$

$$\underbrace{[bg}_{P}D^2 + \underbrace{(hb+cg)}_{Q}D + \underbrace{(ch+ak)}_{R}]x = hf \qquad (=0)$$

use simplified constants →

$$[PD^2 + QD + R]x = hf$$

The characteristic equation to obtain the homogeneous solution y_H is

$$Pr^2 + Qr + R = 0$$

since P, Q and R are known in terms of constants l21 is a quadratic equation in r with roots

$$r_3 = \frac{-Q + \sqrt{Q^2 - 4PR}}{2P}$$

$$r_4 = \frac{-Q - \sqrt{Q^2 - 4PR}}{2P}$$

These r_3 and r_4 are in the general form of the homogeneous solution

$$x_H = c_3 e^{r_3 t} + c_4 e^{r_4 t} + c_6$$

and since the particular solution x_p = constant (because l18: hf = constant) the complete solution

$$x = x_H + x_p = c_3 e^{r_3 t} + c_4 e^{r_4 t} + c_6 + x_p$$

$$x = c_3 e^{r_3 t} + c_4 e^{r_4 t} + c_5$$

thus

$$\frac{dx}{dt} = c_3 r_3 e^{r_3 t} + c_4 r_4 e^{r_4 t}$$

$$\frac{d^2x}{dt^2} = c_3 r_3^2 e^{r_3 t} + c_4 r_4^2 e^{r_4 t}$$

substitute these into equation on l18 above.

$x = f(t)$

$$[PD^2 + QD + R]x = hf$$

$$Pc_3r_3^2e^{r_3t} + Pc_4r_4^2e^{r_4t} + Qc_3r_3e^{r_3t} + Qc_4r_4e^{r_4t} + Rc_3e^{r_3t} + Rc_4e^{r_4t} + Rc_5 = hf$$

$$c_3e^{r_3t}(\underbrace{Pr_3^2 + Qr_3 + R}_{=0 \leftarrow \text{l21, p6}}) + c_4e^{r_4t}(\underbrace{Pr_4^2 + Qr_4 + R}_{=0 \rightarrow}) + Rc_5 = hf$$

constants are equal, so

$$Rc_5 = hf, \text{ or } c_5 = \frac{hf}{R} = \frac{hf}{ch+ak}$$ which are now known constants

Let $\frac{dx}{dt} = 0$ at $t=0$. then from p6 l41

$$\frac{dx}{dt} = 0 = c_3r_3e^0 + c_4r_4e^0$$

$$-c_3r_3 = c_4r_4$$

$$c_4 = \frac{-c_3r_3}{r_4}$$

substitute into l 39, p6

$$x = c_3e^{r_3t} + \left(\frac{-c_3r_3}{r_4}\right)e^{r_4t} + c_5$$

$$x = c_3\left(e^{r_3t} - \frac{r_3}{r_4}e^{r_4t}\right) + \frac{hf}{ch+ak}$$

c_3 is determined by boundary conditions: at $t=0$, $x = x_0$

$$x_0 = c_3\left(1 - \frac{r_3}{r_4}\right) + \frac{hf}{ch+ak}$$

$$c_3 = \left[\frac{x_0 - \frac{hf}{ch+ak}}{(1 - r_3/r_4)}\right]$$

$$\boxed{x = \left[\frac{x_0 - \frac{hf}{ch+ak}}{\left(1 - \frac{r_3}{r_4}\right)}\right]\left(e^{r_3t} - \frac{r_3}{r_4}e^{r_4t}\right) + \frac{hf}{ch+ak}}$$

where x_0 = initial concentration of recycle tanks

$hf/(ch+ak)$ = final concentration of recycle tanks = $\dfrac{(Q_e+Q_r+sV_2)(Q_AC_A)}{(Q_B+sV_1)(Q_e+Q_r+sV_2)+Q_rQ_B}$

r_3 = p6, l25

r_4 = p6, l28

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12800.15	46 / 87	PP(B)-004	5/10/84	

Specific case I : steady state operation

$$x = \left[\frac{x_0 - \frac{hf}{ch+alk}}{\left(1 - \frac{r_3}{r_4}\right)} \right] \left(e^{r_3 t} - \frac{r_3}{r_4} e^{r_4 t} \right) + \frac{hf}{ch+alk}$$

Let x' be concentration in recycle tank at steady state; i.e., $t \to \infty$.
To maintain this concentration, x'

$$x' = \frac{hf}{ch+alk} = \frac{(Q_e + Q_r + sV_2)(Q_A C_A)}{(Q_B + sV_1)(Q_e + Q_r + sV_2) \mp Q_r Q_B}$$

Knowing the desired x' to be maintained, we solve for $Q_A C_A$ lb/hr additive.

$$\frac{(x')\left[(Q_B + sV_1)(Q_e + Q_r + sV_2) \mp Q_r Q_B\right]}{(Q_e + Q_r + sV_2)} = Q_A C_A$$

$x' = 500 \text{ ppm} = .0005$

$Q_B = 569{,}300$ PP(B)-002, p2, l23.

$s = .1/24$ assume 10% overall loss per day

$V_1 = 8{,}444{,}369$ PP(B)-001, p2, l11

$Q_e = 204{,}000$ UOP dwg R-60-0101 (29) thick. UF; no filtrate returned

$Q_r = 581{,}300$ UOP dwg R-60-0101 4×(3) + (24) + (25) water to recycle tanks
4(125,000) + 70,000 + 11,300

$V_2 = 17{,}814{,}805$ PP(B)-001, p2, l35

$Q_B + sV_1 = 569{,}300 + (.1/24)\,8{,}444{,}369 = 569{,}300 + 35{,}185 = 604{,}485$

$Q_e + Q_r + sV_2 = 204{,}000 + 581{,}300 + (.1/24)\,17{,}814{,}805 =$
$= 204{,}000 + 581{,}300 + 74{,}228 = 859{,}528$

$Q_r Q_e = 581{,}300 \times 569{,}300 = 3.30934 \times 10^{11}$

$$\frac{(.0005)\left[(604{,}485)(859{,}528) \mp 3.30934 \times 10^{11}\right]}{859{,}528} = Q_A C_A$$

$302.24 - 192.51 = Q_A C_A = 109.73 \text{ lb/hr additive}$

at 20% concentration, solution is

$$\left(\frac{109.73}{.2} \text{ lb/hr}\right)\left(\frac{1 \text{ hr}}{60 \text{ min}}\right)\left(\frac{1 \text{ gal}}{8.34 \times 1.02 \text{ lb}}\right)$$

$= 1.075$ GPM

(steady-state)

$Q_A C_A = 109.73 \frac{lb}{hr}$ can be used in solution for y at $t \to \infty$

$$y_\infty = \frac{-kf}{ch - ak} =$$

equilibrium concentration for "rest of FGDS"

$$y_\infty = \frac{(-1)(-Q_B)(Q_A C_A)}{(Q_B + sV_1)(Q_e + Q_r + sV_2) - (-Q_r)(-Q_B)}$$

$$= \frac{(569{,}300)(109.73)}{(604{,}485)(859{,}528) - (581{,}300)(569{,}300)}$$

$$= \frac{6.2469 \times 10^{7}}{5.196 \times 10^{11} - 3.309 \times 10^{11}} = \frac{6.25 \times 10^{7}}{1.886 \times 10^{11}} = .000331$$

$= 331$ ppm

Check:

entrainment out $= y_\infty \times Q_e = (.000331)(204{,}000) = 67.57$ lb/hr

oxid & degr in recycle tank $(.0005)(8{,}444{,}369)(\frac{1}{24}) = 17.59$ lb/hr

oxid & degr in rest of FGDS $(.000331)(17{,}814{,}805)(\frac{1}{24}) = 24.57$ lb/hr

total loss = total makeup 109.73 lb/hr ✓

checks with $Q_A C_A = 109.73$ lb/hr analytically from pB

Specific Case II = stop feed & observe decay of concentration

complete solutions are

$$x = \left[\frac{x_0 - \frac{hf}{ch-ak}}{\left(1-\frac{r_3}{r_4}\right)}\right]\left(e^{r_3 t} - \frac{r_3}{r_4}e^{r_4 t}\right) + \frac{hf}{ch-ak}$$

$$y = \left[\frac{y_0 + \frac{kf}{ch-ak}}{\left(1-\frac{r_1}{r_2}\right)}\right]\left(e^{r_1 t} - \frac{r_1}{r_2}e^{r_2 t}\right) + \frac{-kf}{ch-ak}$$

since as $t \to \infty$, $x \to 0$ and $y \to 0$, $\frac{hf}{ch-ak}$ and $\frac{-kf}{ch-ak}$ both $= 0$

Thus

$$x = \frac{x_0}{\left(1-\frac{r_3}{r_4}\right)}\left(e^{r_3 t} - \frac{r_3}{r_4}e^{r_4 t}\right)$$

$$y = \frac{y_0}{\left(1-\frac{r_1}{r_2}\right)}\left(e^{r_1 t} - \frac{r_1}{r_2}e^{r_2 t}\right)$$

Simplifying terms, we have

$$x = x_0\left(\frac{r_3 e^{r_4 t} - r_4 e^{r_3 t}}{r_3 - r_4}\right) = x_0\left[\left(\frac{r_1}{r_1-r_2}\right)e^{r_2 t} - \left(\frac{r_2}{r_1-r_2}\right)e^{r_1 t}\right]_{\text{(see below)}}$$

$$y = y_0\left(\frac{r_1 e^{r_2 t} - r_2 e^{r_1 t}}{r_1 - r_2}\right) = y_0\left[\left(\frac{r_1}{r_1-r_2}\right)e^{r_2 t} - \left(\frac{r_2}{r_1-r_2}\right)e^{r_1 t}\right]$$

Evaluate r_1, r_2, r_3, r_4 to obtain numerical solution

from p6, $r_3, r_4 = \dfrac{-Q \pm \sqrt{Q^2 - 4PR}}{2P} = \dfrac{-(hb+cg) \pm \sqrt{(hb+cg)^2 - 4(bg)(ch-ak)}}{2bg}$

from p 3, $r_1, r_2 = \dfrac{-\beta \pm \sqrt{\beta^2 - 4\alpha\gamma}}{2\alpha} = \dfrac{-(hb+cg) \pm \sqrt{(hb+cg)^2 - 4(bg)(ch-ak)}}{2bg}$

Therefore $r_1 = r_3$ $r_2 = r_4$. Evaluate r_1, r_2

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(feed = 0)

$$r_1, r_2 = \frac{-B \pm \sqrt{B^2 - 4\alpha\gamma}}{2\alpha}$$

$$= \frac{-(cg+bh) \pm \sqrt{(cg+bh)^2 - 4(bg)(ch-ak)}}{2bg}$$

$$= -\left(\frac{c}{2b} + \frac{h}{2g}\right) \pm \frac{1}{2}\sqrt{\frac{c^2g^2 + 2cgbh + b^2h^2 - 4bgch + 4bgak}{b^2g^2}}$$

$$= -\left(\frac{c}{2b} + \frac{h}{2g}\right) \pm \frac{1}{2}\sqrt{\frac{c^2}{b^2} + \frac{2ch}{bg} + \frac{h^2}{g^2} - \frac{4ch}{bg} + \frac{4ak}{bg}}$$

$$= -\left(\frac{c}{2b} + \frac{h}{2g}\right) \pm \frac{1}{2}\sqrt{\frac{c^2}{b^2} - \frac{2ch}{bg} + \frac{h^2}{g^2} + \frac{4ak}{bg}}$$

$$= -\left(\frac{c}{2b} + \frac{h}{2g}\right) \pm \frac{1}{2}\sqrt{\left(\frac{c}{b} - \frac{h}{g}\right)^2 + \frac{4ak}{bg}}$$

Then in terms of known values on p 2 ℓ 33 to 42 :

$$= -\left(\frac{Q_B + sV_1}{2V_1} + \frac{Q_e + Q_r + sV_2}{2V_2}\right) \pm \frac{1}{2}\sqrt{\left(\frac{Q_B + sV_1}{V_1} - \frac{Q_e + Q_r + sV_2}{V_2}\right)^2 + \frac{4(-Q_r)(-Q_B)}{V_1V_2}}$$

Using abbreviations $B = \frac{Q_B}{V_1}$, $E = \frac{Q_e}{V_2}$, $R = \frac{Q_r}{V_2}$

$$= \left(-\tfrac{1}{2}\right)\left[(B+E+R+2s) \pm \sqrt{(B+s-E-R-s)^2 + 4RB}\right]$$

$$= \left(-\tfrac{1}{2}\right)\left[(B+E+R+2s) \pm \sqrt{(B-E-R)^2 + 4RB}\right]$$

Numerically $B = \frac{Q_B}{V_1} = 569{,}300/8{,}444{,}369 = .067418$ ①

$E = \frac{Q_e}{V_2} = 204{,}000/17{,}814{,}805 = .011451$ ②

$R = \frac{Q_r}{V_2} = 581{,}300/17{,}814{,}805 = .032630$ ③

$s = \frac{.1}{24} = .004167$ ④ 10% per day losses

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(feed=0)

$$r_1, r_2 = \left(-\tfrac{1}{2}\right)\left[(B+E+R+2S) \pm \sqrt{(B-E-R)^2+4RB}\right]$$

$$= \left(-\tfrac{1}{2}\right)\left[\,.119832 \pm \sqrt{.000544 + .008799}\,\right]$$

$$= \left(-\tfrac{1}{2}\right)(\,.119832 \pm .096664\,) =$$

$$r_1 = -.108248$$

$$r_2 = -.011584$$

so, $\left(\frac{r_1}{r_1-r_2}\right) = 1.119838$, and $\left(\frac{r_2}{r_1-r_2}\right) = .119838$

rewriting solutions from p10 ll 27 to 32

$$\frac{x}{x_0} = \frac{y}{y_0} = \left[\left(\frac{r_1}{r_1-r_2}\right)e^{r_2 t} - \left(\frac{r_2}{r_1-r_2}\right)e^{r_1 t}\right]$$

$$= 1.119838\,e^{-.011584t}\ (4) - .119838\,e^{-.108248t}\ (5)$$

day	hrs t	$\frac{x}{x_0} = \frac{y}{y_0}$		x	y
0	0	1.0		500 ppm	331 ppm (p9 case I)
1	24	0.8391	= .848036 − .008919	420 ppm	278 ppm
2	48	0.6415	.642205 − .000664	321 ..	213 ..
3	72	0.4863	.486332 − .0000494	243	161
5	120	0.2789	.278901 − (v. small)	139	92
7	168	0.1599	.159944	80	53
10	240	0.0695		35	23
14	336	0.0228		11 ppm	8
Y_2	12	0.9418	.974506 − .032693	471 ppm	

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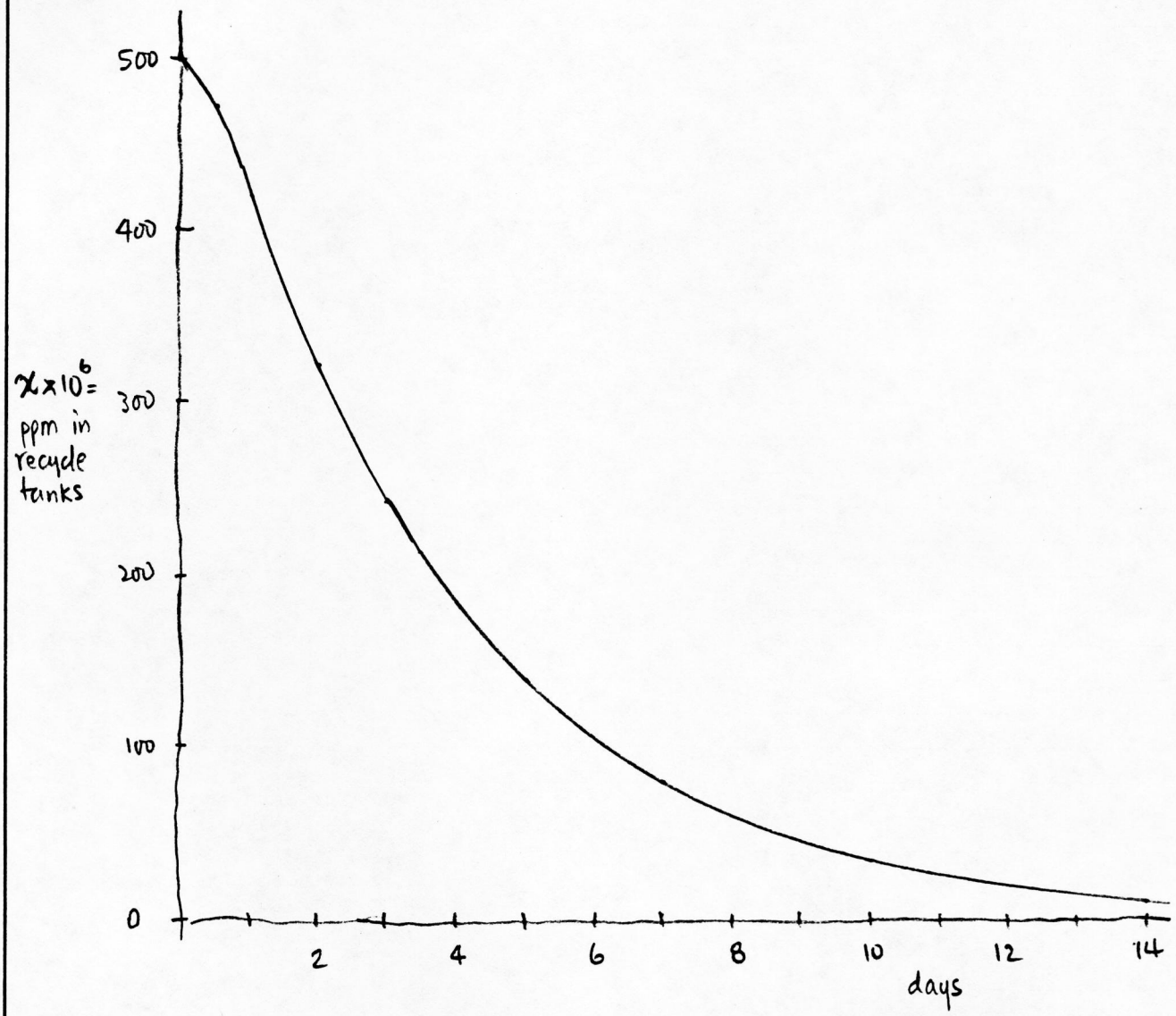
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